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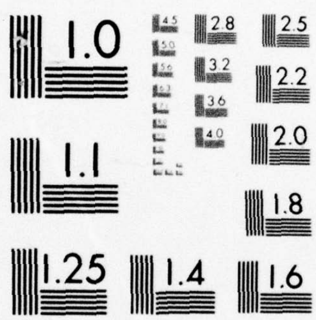

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TECHNICAL REPORT

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ADAPTIVE TRAINING OF PERCEPTUAL MOTOR SKILLS: ISSUES, RESULTS AND FUTURE DIRECTIONS

GAVAN LINTERN, DANIEL GOPHER

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AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
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Gavan Lintern

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FOREWORD

This review of the field of adaptive training (AT) was done as a part of a research program being conducted at the Aviation Research Laboratory, University of Illinois, sponsored by the Air Force Office of Scientific Research. The review has two aims; the first is to assess AT as a method for teaching control skills, and the second is to establish a conceptual framework that will allow a detailed analysis of adaptive manipulations and their influence on skill acquisition.

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INTRODUCTION

Adaptive training (AT) is a procedure in which the training schedule is individualized by varying task difficulty through a graded series of steps at a rate that is related to the trainee's speed of learning. A demanding task is initially simplified in some manner, and the trainee's performance is monitored so that task difficulty can be gradually increased as he develops proficiency. AT is based on the intuitively appealing assumption that a demanding task can be learned more efficiently if it is presented throughout training at a level of difficulty that is optimally matched to each individual's current ability (Kelley, 1969 b).

Individualized training schedules can be justified theoretically by the widespread evidence of substantial individual differences in ability and rates of learning (Fleishman, 1967). The use of task simplification, as an aid to learning is supported by the view among motor skill theorists, that complex skills are composed of simple skills (Fitts and Posner, 1967). The continuous match of task difficulty with the trainees concurrent level of skill (Kelley, 1969 b), or his orderly progress through a series of subtasks that are graded in complexity (Gaines, 1967) should therefore provide a more efficient training experience then the traditional fixed task methods (FT).

From a technical viewpoint, adaptive procedures are becoming more feasible as a result of the considerable advance in mini and micro computer technology. In the new generation of computer-supported systems, computer algorithms that process information about the operator's behavior can directly affect the nature of the man-machine interaction. Thus real time automated applications and complex, individualized training systems are becoming more economical and easier to implement. The human factors community recognized the potential value of computer supported systems in the field of training almost two decades ago (Hudson, 1962). Since then AT has been investigated by human factor specialists, primarily as a means of facilitating the acquisition of perceptual motor skills.

The bulk of AT research has been conducted with a dominant applied orientation and with a strong aviation bias. Most of the influential experiments have been reported in establishment publications and have rarely been published in scientific journals. The dominant applied orientation has produced a substantial body of data, but little systematic theorizing about the process of skill acquisition under the adaptive paradigm, and meager discussion about the relationship of those data to other theoretical conceptions about skill acquisition. As a result, the work on AT has hitherto failed to produce a comprehensive review of research or a critical evaluation of the concept. In view of the fact that AT systems have been designed into some aircraft simulators (Caro, 1969), presumably at some added expense, a comprehensive review of the research seems overdue. Our review represents an effort to correct this deficiency by describing the basic AT paradigm, describing and evaluating the research, and establishing a systematic framework to guide future research.

In describing and evaluating the research we have initially emphasized the pragmatic implications of the data by concentrating on criteria such as training time, transfer of training, and training costs, as is consistent with the tendency demonstrated in published reports of research. Nevertheless the experimental data, in addition to reflecting on the training effectiveness of adaptive techniques, could inform us about the process of skill acquistion. A better understanding of this process, whether gained from AT or other research, is likely to contribute to improved methods of skill training. The review addresses this aspect in part by drawing on AT and other motor skill theory and data to determine the influence of various features of the adaptive paradigm on the developing motor skill. Thus our review has two aims: the first is to assess AT as a method for teaching control skills, and the second is to establish a conceptual framework that will allow a detailed analysis of adaptive manipulations and their influence on skill acquisition.

FEATURES OF THE ADAPTIVE TRAINING PARADIGM

Adaptive training incorporates a closed loop system in which task difficulty is automatically adjusted in relation to some index of student performance. The adaptive variable is the task feature that is adjusted to change the difficulty, and its value reflects the trainee's current performance level. A computer algorithm determines the adaptive variable's relationship to student performance so that, as the trainee improves, task difficulty increases to maintain the index of performance within predetermined limits. The amount of learning is operationally defined by the change in the adaptive variable. The conditions of training are operationally defined in the computer algorithm which specifies the nature and range of the adaptive variable, the limits of the performance index, the period over which performance is averaged to provide an index for adjusting the task difficulty, and the number and size of steps in difficulty.

All of the AT experiments to be reviewed examined the acquisition of tracking skills. Tracking behavior has been extensively investigated both in human factors laboratories and in operational situations. Comprehensive discussions of tracking behavior by Adams (1961), Frost (1972), Pew (1974), Poulton (1974), and Sheridan and Ferrel (1974) are available. The schematic diagram of a typical tracking task in figure 1 shows the important features of operational and synthetic laboratory tracking systems. In any tracking task the operator must follow a representation of a forcing function by manipulating a control mechanism.

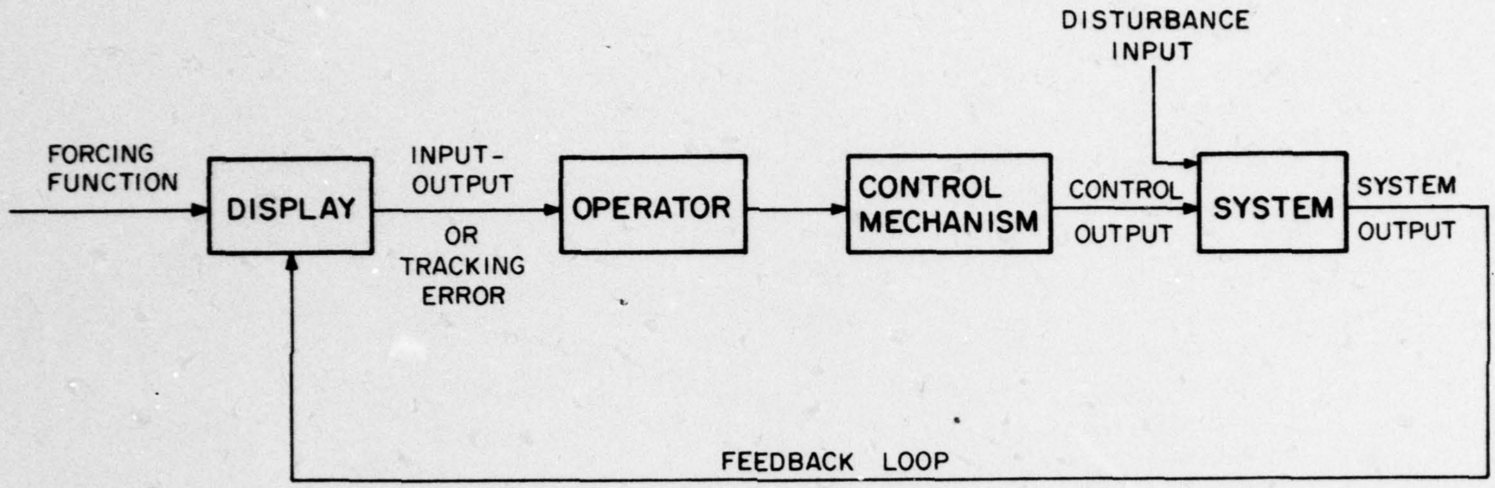

Figure 1. Schematic of a Typical Tracking Task.

The control mechanism generates an output signal that affects the behavior of the system, as can a random disturbance applied directly to the system. The difference between the system output and the forcing function is the tracking error which is, for operational systems, the discrepancy between the actual system track and the track defined by the forcing function, and for synthetic systems, the discrepancy between a controlled cursor that represents system output and a target cursor that represents the forcing function. Although AT seems relevant to many skilled behaviors, the exclusive emphasis on tracking is consistent with a predominant interest, among human factor specialists, in vehicular control behavior.

The general experimental paradigm for comparing adaptive and non-adaptive methods includes a control group and one or more experimental groups. The control subjects experience a non-adaptive schedule in which they practice a criterion task throughout training. The experimental subjects first practice a relatively simple task which adapts towards the more demanding criterion task as the subjects become more skilled. In some experimental designs, control and experimental subjects transfer to a fixed task on which their skill is assessed. Forcing function parameters, system characteristics, and display characteristics have been used as adaptive variables. The effectiveness of AT has been judged on the basis of indices such as amount of learning in a given time, skill retention over an extended period, the time taken to learn specified skills, and transfer of skill to similar tasks. From the results of the experiments following this paradigm many experimenters have concluded that adaptive training is superior to fixed training (Caro, 1969; Hudson, 1962, 1964; Kelley, 1969 b; Lowes, Ellis, Norman and Matheny, 1968; Norman, 1973). A following section of this review will evaluate the AT research in order to assess whether confidence in the effectiveness of AT is well founded.

In discussing the research, it has been necessary to reconcile the different terms that have been used for similar adaptive manipulations. Where confusion might arise the terminology used by Frost (1972) and Wickens (1976) has been accepted because it is systematic and is consistent with general usage.

Adaptive manipulations can be usefully classified as perceptual, response, or feedback variables. Perceptual manipulations are those resulting from changes in forcing function or disturbance inputs. Any transformations on the forcing function or disturbance inputs will be paralleled by similar transformations in the displayed input. An operator who is performing efficiently can maintain his performance in the face of such input variations by applying the transformation perceived in the displayed information to his own control behavior. Response manipulations are changes in system dynamics. Although the required transformations between old and new control behavior are unambiguously defined by the changes in system dynamics they are, in contrast to those resulting from forcing function or disturbance manipulations, not directly represented in the display. In particular, similar patterns of displayed information will require quite different response patterns. For feedback variables, inputs and system dynamics are unchanged, and variations in the quality of the displayed information are used to adjust task difficulty.

Response Variables

(1) System order refers to the transformation between control displacement and the subsequent displacement of the controlled cursor. A zero order (position) system is one in which a step control displacement is transformed into a step displacement at system output. In a first order (velocity) system, a similar control displacement will change system output at a constant rate, and in a second order (acceleration) system, at a constant acceleration. A third order system that constantly accelerates (jerks) the sytem output in response to a step control displacement, is the highest order that has been used in AT. Human operators find tracking more difficult as the order of the system is raised.

System order can be changed in discrete steps, or can be varied continuously by changing the ratio of higher to lower order components. It has been adapted in six experiments (Briggs, 1961; Crooks, 1973; Gopher, Williges, Williges and Damos, 1975; Hudson, 1962, 1964; Norman, Lowes and Matheny, 1972). Manipulations of system order are often referred to as either aiding or quickening. The important technical distinction between quickening and aiding, as applied to operational systems, becomes trivial when applied to synthetic systems. A synthetic system is termed as a aided if displayed error is recorded, but as quickened if system error is recorded (Norman et al., 1972). As these two indices of error are almost certainly highly correlated in a synthetic system, aiding and quickening will be considered in the discussion of system order.

(2) System lag is measured by the delay of a perceptible system response to control inputs. Tracking becomes more difficult as lag increases (Poulton, 1974). A decrease in difficulty with increasing lag, observed by Rockway (1954) has been explained by Poulton (1974) as a range affect. Lag has been adapted in two experiments (Norman, 1973; Norman et al., 1972), but on both occasions, only after initial increases in task difficulty had been achieved by adapting gain. This procedure was suggested by Matheny and Norman (1968) who observed that short lags facilitate skill acquisition and that task difficulty is directly proportional to gain. They recommended an adaptive manipulation that initially maintained lag at some small value while task difficulty was increased by increasing gain to its criterion value. After that had been accomplished, lag could be increased towards its criterion value to further increase task difficulty.

(3) System gain is defined as the ratio of displacement in system output to control displacement. The relationship of gain to difficulty is non-monotonic in that both high and low gain systems can be more difficult to use than medium gain systems. High gain systems require fine adjustments, while performance

with low gain systems can be limited by the maximum force or displacement the operator can achieve. Gain has been adapted in four experiments (Gopher _et al._, 1975; Hudson, 1964; Norman, 1973; Norman _et al._, 1972), and in all of them, difficulty has been increased by increasing gain. Two of the gain manipulations (Norman, 1973; Norman _et al._, 1972) have been made in conjunction with manipulations in system lag.

(4) System stability describes the tendency of a system to achieve or regain equilibrium. A system is stable if a small temporary input causes only a temporary change in output. The property of stability (or instability) is a consequence of the presence of a feedback loop - with positive feedback systems tending to be more unstable then negative feedback systems. Unstable systems are difficult to control, and normally yield poor tracking performance (Wickens, 1976). This variable has been adapted in two experiments (Hudson, 1964; Bancroft and Duva, 1969).

(5) Damping ratio refers to the attenuation of a second order system's response to its resonant frequencies. High damping ratios produce a sluggish system, and low damping ratios produce an unstable system, both of which are difficult to track. Gaines (1967), who reduced damping ratio from an intermediate to a low value to increase task difficulty, is the only investigator to adapt this variable.

Perceptual Variables

(1) Forcing function amplitude refers to the amplitude of the random or random appearing disturbance applied at the system input. Increases in this variable increase any or all of displacement, velocity, and acceleration of the target, and thus increase tracking difficulty. It has been adapted in five experiments (Gaines, 1967; Kelley, 1966; Lowes et al., 1968; Norman et al., 1972; Wood, 1969).

(2) Forcing function bandwidth refers to the range between the lower and the upper cut-off frequencies contained in the random appearing disturbance applied at the system input. Increases in this variable increase tracking difficulty. It has been adapted in two experiments (Gopher et al., 1975; Williges and Williges, 1976).

Feedback Variables

(1) Intrinsic information about the effects of responses can be supplemented with artificial cues that are more informative. Such augmenting cues can simplify a control task (Armstrong, 1970 b; Eisele, Williges, and Roscoe, 1977; Smith, Pence, Queen and Wulfeck, 1974) and can therefore define a dimension of difficulty. Augmenting cues that are programmed to be available only when control errors exceed a certain criterion are inherently adaptive in that, as the subject improves, he obtains less assistance from them. Several studies (Gilson and Ventola, 1976;

Gordon and Gottlieb, 1967; Smith, et al., Williams and Briggs, 1962) have tested augmented feedback that is inherently adaptive.

In order to judge the efficiency of AT, it is necessary to establish relevant and comparable criteria for the several experimental design variations that have been used. The simplest design is one in which subjects learn a task by practicing it in an adaptive or a fixed mode. Training efficiency is assessed by comparing performance levels after a pre-determined period of training or by comparing amounts of training needed for groups to achieve a performance exit criterion.

In the more common transfer of training design subjects generally transfer to a fixed task after experience with either an adaptive or a fixed pre-transfer task. This design is analogous to the situation in which operators learn in a simulator that permits adaptive manipulations, and then transfer to the operational system in which adaptive manipulations are not feasible. For experiments in which pre-transfer training is equal for all groups, training efficiency can be assessed by examining performance levels after a set amount of experience with the transfer task, or by comparing trials to criterion on the transfer task. Data from an alternate design in which subjects practice the pre-transfer task to exit criterion produce results that are difficult to interpret because amounts of pre-transfer training invariably differ between groups: amount and conditions of pre-transfer training are therefore confounded. It is possible however, to unconfound these two factors by examining total pre-transfer and transfer training required to exit from the transfer task.

RESEARCH

Although this review draws only from the literature on adaptive training, the similarity between AT and the better established programmed instruction technique was recognized. In fact the principles of AT are so similar to those of programmed instruction that there is no apparent useful distinction between the two methods (Roscoe, 1974). The distinction that AT is specific to perceptual and motor skills while programmed instruction is specific to cognitive skills (Wood, in McGrath & Harris, 1971), does not conform to common usage. Programmed instruction has been used to teach perceptual skills (Swets, Millman, Fletcher and Green, 1962; Moore and Goldiamond, 1964) and AT has been used to teach cognitive skills (Walter, Rivers, King and Hansen, 1970). The distinction therefore seems artificial and is undesirable because it could discourage investigators preferring either term from taking account of relevant theory and research generated by investigators preferring the alternate term. Nevertheless, a search of the programmed instruction literature failed to reveal any relevant motor skill research. Thus only experiments from the literature on AT are included in the review.

The AT studies using response and perceptual variables have been grouped together in the discussion of research because some of the studies manipulated both types of variables. It was not possible to further subgroup these studies in terms of common experimental characteristics. In lieu of a more appropriate classification, we first present the early studies in chronological order. These studies, which were undertaken in various laboratories, established the research interest in AT. Since 1969 the research involving response and perceptual manipulations has been centered in two groups: Norman and his associates, and the Aviation Research Laboratory at the University of Illinois. The work from each of these groups is presented as a separate body of research. Work with feedback variables is described after the section describing the tests of response and perceptual manipulations.

Response and Perceptual Variables

An investigation of tracking skills by Briggs (1961) provided some impetus for AT research. Procedures developed in that experiment and the results obtained influenced the design and direction of later experiments. In Briggs' experiment, groups of subjects who learned a one-dimensional second-order tracking task by first practicing a zero-order and then a first-order task, were compared to a control group that practiced only the second-order task. The experimental groups transferred to a higher-order task when they reduced their tracking error to a specified value. Briggs compared the error scores of the control and experimental groups on successive trials, starting at each group's first trial on the second-order task. There were no long term differences between groups although experimental groups showed an early but temporary superiority over the control group. Briggs concluded that experience with the lower-order tasks had facilitated the acquisition of the second-order task.

The benefit of experience with a lower-order task was slight. The advantage shown by the experimental groups over the control group disappeared after eight 30-second trials. Furthermore, the experimental groups were given at least ten 30-second practice trials more than the control group at each point of comparison. A relevant test of AT would compare the groups when they had experienced equal amounts of tracking practice. Such comparison shows that the initial advantage lay with the control group. Nevertheless, a subsequent discussion of these data (Hudson, 1964) has erroneously established this experiment as one that demonstrates an advantage for AT.

Hudson (1962, 1964) has reported two investigations of AT. In the first study he compared the performance of two adaptively trained groups to a non-adaptively trained control group. The experimental groups practiced a two-dimensional compensatory tracking task in which difficulty was adapted by varying the percentage of first, second, and third order components. The time constant, defined for the adaptive tasks as the interval over which tracking error was integrated, differed for the two experimental groups. The control group practiced a fixed third-order version of the same tracking task. All groups were allowed nine 20-minute training sessions. After every training session, each group was tested for five minutes on the fixed third-order task that the control group had practiced. The experimental group with the longest time constant exhibited lower error scores during the test sessions than either of the other two groups. From these data, Hudson (1962) concluded that some adaptive/

manipulations are more efficient than the traditional fixed difficulty manipulations.

The conclusions to be drawn from these data are weakened by doubts about the experimental method. The tracking system was so unstable that the moving cursor could disappear from the screen if the subject lost control of it. When this occurred the experimenter would reset the cursor for the subject to continue tracking. Hudson (1962) did not report how long the cursor would remain off the screen, nor whether the periods during which the subject waited for its return were a part of the 20 minute practice. Control subjects who practiced the most difficult task would presumably have lost control more frequently during training than experimental subjects. If out of control time was included in the practice time, control subjects may have had sufficiently less experience at tracking to account for the performance difference between the control group and the best experimental group. Furthermore, Gopher and Wickens (1975) have suggested that the discontinuities associated with the disappearance of the cursor during loss of control can disrupt tracking performance. Either or both of these factors would explain the performance advantage shown by the best adaptive group.

In a similarly designed experiment Hudson (1964) used the same apparatus to compare six adaptively trained groups with one non-adaptively trained group. The experimental groups practiced a tracking task in which either system order, gain, or stability was adapted either automatically or was changed manually by the experimenter. The control group practiced a third-order tracking task. After a pre-determined training period, all subjects were tested on the third-order task that had been used for training the control group.

Performance during test trials was related to the difficulty of the training task, where difficulty was a function of the number of times the subject lost control of the tracking system during the training period. The groups that experienced the medium difficulty training task performed best. Some of the differences were statistically reliable. Although Hudson (1964) again seems to have demonstrated that some adaptive manipulations are more efficient than non-adaptive manipulations, the confounding effects of frequent control losses detract from the value of the result. Thus Hudson's (1962, 1964) research has not provided the substantial support for the application of AT that it might, at a preliminary reading, appear to.

The next experiment to be discussed was reported by Kelley (1966) who has been a leading advocate for AT (Kelley, 1969 b; McGrath and Harris, 1971). Amplitude of the forcing function was chosen as the adaptive variable. In this experiment, two subjects were alternately given adaptive and non-adaptive trials on a two-dimensional, second-order tracking task, so that it was not possible to compare adaptive and non-adaptive training at any stage. Kelley recognized that the experiment was limited in this regard:

> "These data say nothing about the effectiveness of adaptive training compared with fixed training." (Kelley, in McGrath and Harris, 1971, p. 10)

He nevertheless used this experiment to support his confidence in the value of adaptive training (Kelley, 1969 b). The data demonstrated a linear increase in performance for adaptive trials and a curvilinear increase for non-adaptive trials. Because the subjects alternated between adaptive and fixed trials the comparison is merely one of two methods of measuring the same level of proficiency. Kelley (1969 b) apparently assumes that learning is a linear process and a measure that exhibits a linear increase is therefore more appropriate. However both types of measures could conceivably be useful in different circumstances. The strength of Kelley's adaptive measure of performance lies in its demonstrated reduced variability in comparison to the conventional measure (Kelley, 1969a). The potential of the adaptive measure to reliably discriminate small performance differences could be useful in many training and testing applications. Nevertheless, this argument has little to do with the evaluation of adaptive training and Kelley's experiment has not demonstrated any training advantages for the method.

The first clear empirical support for AT was obtained by Gaines (1967) from an experiment in which subjects learned a third-order tracking task. The moving cursor was controlled with a dual push-button system. The subject could jerk the moving cursor to the right by pressing one button and jerk it to the left by pressing the other. The system was unusual in that the directional effects of both buttons reversed after each control movement. During the training phase, control subjects practiced either a fixed, difficult task or a fixed, easy task. Adaptive subjects practiced a task in which the damping ratio and the amplitude of the forcing function were adjusted to vary difficulty. Control and adaptive subjects were then tested with a series of tasks that included the difficult and easy tasks used to train the control groups.

The adaptive groups exhibited substantially lower error scores than the fixed-task groups throughout the test phase. It is particularly relevant to this review that the adaptively trained groups were more skilled on the fixed, difficult task during the test phase than were the groups that had trained with that task. This experiment clearly supports the AT principle that learning can be more efficient if trainees are allowed to learn a difficult task by first practicing a graded series of simpler versions of the task. Nevertheless the generality of this finding is in doubt. The skills required for the push button controller used by Gaines are probably very different from those required for the stick or wheel controllers found in other AT research and in most vehicles. Push button control seems to emphasize cognitive skills in contrast to motor skills. On the other hand, wheel and stick controllers require series of responses that approximate complex patterns of continuous movement. The magnitude, duration, and direction of control forces must be precise and must be integrated into an appropriate sequence. Although Gaines' data are encouraging, similar findings from experiments that examine skills more typical of operational control tasks are needed to support AT.

In a simple comparison of adaptive and fixed training Wood (1969) trained subjects on a two-dimensional, second-order tracking task. Amplitude of the forcing function, which was selected as the adaptive variable, was adjusted so that the experimental group maintained a constant RMS error. A control group was trained after the adaptive group, and the difficulty of their task was increased in five discrete steps over the five training sessions. The five levels were obtained from the median forcing function amplitude experienced in each of the adaptive group's five sessions. Wood therefore provided similar training experiences for both groups. In the transfer task subjects were tested with five levels of forcing function amplitude. The non-adaptively trained group was superior to the adaptively trained group at all transfer conditions.

Although Wood (1969) concluded, from these data, that AT was less effective than fixed training (FT), Kelley (McGrath and Harris, 1971) claimed that Wood's control group had experienced discrete adaptive training so that Wood had really compared two adaptive schedules. In support of Kelley's claim, it could be argued that the groups had been randomly selected and were theoretically equivalent. The control group might therefore be considered as a discretely adapted group where the rate of adaptation was based on the performance of a similar group. Nevertheless adaptation on the basis of group performance is not generally accepted in AT methodology. Kelley (1969b) has stressed that one of the strengths of AT is that task difficulty adapts to the individual's ability by maintaining his error rate within optimal limits. Wood's experiment seems to be a fair test of AT, and it is one that has demonstrated that non-adaptive methods can be more effective.

An experiment by Bancroft and Duva (1969) examined the effects of the error limit that was used to control the adaptive logic. These experimenters proposed that subjects who had to track within smaller error limits before they proceeded to the next step in the adaptive schedule, would learn more or less efficiently than subjects whose progress was controlled by larger error limits. A control group was included so that AT could be compared with FT. Four groups of subjects were trained on a two dimensional, third-order, compensatory tracking task. System stability was adapted through six levels of difficulty in the three adaptive conditions. Adaptive subjects graduated to a higher level of difficulty when their integrated error over 4 thirty-second trials was within the error limit specified for their adaptive condition. The three adaptive groups differed only in regard to the error limit that controlled their progress through the adaptive schedule. The control group practiced only the most difficult version of the task. All subjects trained for 270 thirty-second trials and transferred to the most difficult version of the task for 20 thirty-second trials.

No statistically reliable differences were found for tracking error or for number of control losses, either in the training data or in the transfer data. Therefore the experiment failed to show any strong support for AT and did not effectively discriminate the effects of the variable error limits. Nevertheless Bancroft and Duva (1969) suggested that the trends in the data favored the adaptive schedules, and did demonstrate the differential effectiveness of the three error limits. In some circumstances their conclusions from statistically unreliable data might be considered as tentative support for AT. It could be argued that subjects were trained for so long that real experimental effects may have been masked because all subjects approached maximum performance.

Observation of the training data supports this contention. The three experimental groups graduated to the most difficult task with an average of more than 100 practice trials remaining, and appeared to achieve stable performance with an average of at least 60 practice trials remaining. That something was wrong is clearly shown by the failure of the training data to demonstrate statistically reliable performance differences between conditions that varied in average level of difficulty. The trends in the training data were in the expected direction and similar trends observed in the transfer data might also reflect real differences. Nevertheless, their probable cause is debatable. Data supplied by Bancroft and Duva show that subjects in the fixed group lost control of the system more frequently during training than did subjects in the adaptive groups. Furthermore, the poorer adaptive groups lost control during training more often than the better adaptive groups. The loss of control problem has already been discussed in the analysis of Hudson's work (1962, 1964). To summarize that discussion, the time taken for the apparatus to reset after loss of control may reduce effective training time and the discontinuities associated with loss of control might disrupt tracking performance. These data do not provide even tentative support for AT.

In the first of a series of AT experiments by Norman and his associates, subjects were taught to maintain constant apparent altitude in an aircraft simulator (Lowes et al., 1968). Forcing function amplitude was chosen as the adaptive variable. A control group and an adaptive group were trained with an equal number of trials blocked over five sessions. Forcing function amplitude was fixed at a low value for the control group's first training block, and was successively incremented for the subsequent training blocks. The forcing function amplitude for the adaptive group was allowed to vary between the lowest and the highest values used in the experiment. The forcing function amplitude experienced by an adapted subject at any given time depended on his own current control performance.

After they had completed the five training blocks, control and adapted subjects were tested with the intermediate amplitude of forcing function that had been used in the control group's third training block. The test block error scores of the adaptive group were reliably lower than those of the control group. Although Lowes et al. concluded from these data that AT is superior to FT, an alternative and more plausible explanation is possible. The average forcing function amplitude assumed during the adaptive group's training trials, by virtue of the adaptive logic, approximated the value used in the test blocks. Thus the adaptive subjects may have performed the transfer task more efficiently than the control subjects merely because their training experience more closely approximated the test conditions. This alternative explanation does not permit this experiment to stand as a worthwhile test of AT.

To follow up this work Noman, Lowes and Matheny (1972) used a transfer of training design to compare the performances of six experimental and two control groups of subjects in maintaining level pitch in an aircraft simulator. Three adaptive variables were considered: forcing function amplitude, system order, and a combination of system gain and lag in which gain was adjusted during early training and lag adjusted during later training. Six experimental groups were formed so that each variable could be adapted either automatically or could be adjusted by the experimenter while the other variables were maintained at their criterion values. The adaptive variable in the automatic groups varied continuously until it reached its criterion value, which was used as the exit criterion for the subjects training under that condition.

The adaptive variables were adjusted twice in the manual conditions, and the second adjustment was to the criterion value. Subjects exited from the pre-transfer task when they could perform the most difficult version of the task within a specified error tolerance. The six experimental groups transferred to a task that differed from the final form of the pre-transfer task only in that all variables remained fixed at values different from those used in the pre-transfer task. Two control groups were included in the experiment. The first was treated similarly to the experimental groups, except that all variables remained fixed at their criterion values throughout training. The second group practiced only the transfer task.

Norman <u>et al</u>. examined the number of trials taken to achieve the exit criterion on the pre-transfer task. These data showed that the group trained with manually adapting system order learned more slowly than any other group, but did not reveal any other differences between adaptive and non-adaptive groups. The total training and transfer trials index appeared to follow closely the trend of the training trial index, but it was not statistically tested. The authors relied on a transfer trials index to test their adaptive techniques. A comparison of adaptive groups with the control group that had received no pre-transfer training, showed a statistically reliable advantage for all adaptive conditions over the non-adaptive condition. However this was not a reasonable test of AT because, as noted earlier in this review, amount and type of training are confounded in transfer data for which pre-transfer training is not equalized. Notwithstanding the claim of Norman et al., this experiment has also failed to demonstrate any advantage of AT.

Norman (1973) used a similar experimental design to extend the research reported by Norman et al. (1972). During the training phase of this experiment subjects learned to control the pitch and roll of a low performance aircraft simulator as it was buffeted by simulated gust turbulence. When subjects could control pitch and roll within pre-specified error limits, they transferred to a simulation of a high performance aircraft that was also buffeted by gust turbulence, and practiced that to the same criterion. The adaptive variable was the same combination of system gain and lag used in the previous experiment. It was automatically increased towards its criterion value as the subject's control performance improved. Two independent variables were tested. Five different performance measurement intervals were used to define one independent variable. The other was defined by two variations in high frequency components of the forcing function. Two control groups were used; one practiced only the high performance simulation to criterion and the other practiced the fixed version of the low performance simulation to criterion before transferring to the high performance simulation.

Subjects were allowed only twenty trials in which to achieve criterion performance on the pre-transfer task and to achieve a similar standard on the transfer task. Those subjects who were unable to satisfy these requirements within the twenty trial limit were classified as failures and dismissed from the experiment. Norman continued to test new subjects until six had satisfied the performance requirements in each control and experimental group.

The experiment was designed to conform to a common pilot training paradigm in which a trainee pilot learns control skills in a simulator and then transfers to the parent system. In this experiment the parent system was also simulated. Norman developed a cost-of-training index in which the time spent on the parent system simulator was assumed to be five times as expensive as time spent on the training simulator. The cost of training each group's failed subjects was added to the cost of training the six passing subjects in that group. A comparison of the experimental and control groups on the basis of the cost index showed that some adaptive groups were less expensive to train than the control groups. The differences were statistically reliable.

The validity of Norman's cost of training index is suspect. The statistical reliability of the results was largely due to the procedure of failing subjects who did not complete the experiment within 20 trials. Those groups with many failed subjects invariably received a high rating on the cost of training index. The number of failures per group, which ranged from zero to five, showed no systematic trend. The apparent randomness of the distribution of failues and the substantial influence that failures had on cost of training seem to invalidate the cost index as a basis for comparing groups. In addition, the seemingly arbitrary costing of parent system time as five times more expensive than training system time can be questioned. These uncertainties about the design and analysis of the experiment are serious enough to preclude it as a suitable test of AT.

In the first of a series of experiments from the Aviation Research Laboratory at the University of Illinois, Crooks (1973) tested four adaptive methods and one non-adaptive method of teaching a two dimensional tracking task. The ratio of second-order to first-order components in the system was used as the adaptive variable. The second-order component for the four adaptive groups was initially set at 30%, and subjects practiced the task until it had reached the exit criterion of 80%. The adaptive logic for three of the adaptive groups increased the second-order component if the subjects tracked within a prespecified error limit and decreased it if they tracked outside of that limit. The three groups differed in that the prespecified error limits remained constant throughout training for one group, increased as the subject improved in another group, and decreased as the subject improved in the third group. The prespecified error limits for the fourth adaptive group remained constant throughout training. This group differed from the other adaptive groups in that the second-order component of the task could not decrease if subjects tracked outside the error limit. The two changing error limits approached the fixed error limits used by the other groups so that, at exit criterion, subjects from the four groups were performing an identical task. Control subjects in the non-adaptive group practiced the task with a fixed 80% second-order component and exited from it when they reduced their error to the final value used in the adaptive regimes.

Number of trials to achieve the training task exit criterion was established as the primary dependent variable. When tested against this dependent variable, the non-adaptive group was as successful as the adaptive group that had not been permitted any decreases in the acceleration component when they exceeded the error limit. The three remaining adaptive groups required more trials to achieve exit criterion. Two other dependent variables, one a transfer task and the other a retention task, did not reveal any differences among the five groups. Not only did this experiment fail to demonstrate any advantage of AT, but also appeared to demonstrate that some adaptive manipulations could retard skill acquisition.

A subsequent experiment from the same laboratory used a two dimensional tracking task to examine three adaptive variables (Gopher et al., 1975). Frequency of forcing function, system gain, and system order were increased adaptively by themselves, in pairs and together in seven different training conditions. In one additional training condition the three variables remained fixed. For training conditions in which they did not adapt, variables remained fixed at the average adaptive values achieved in a preliminary study by five flight-naive subjects in their fourth five-minute period on a fully adapting task. Subjects in the main study were trained over five three-minute sessions. They were transferred to eight minutes of continuous tracking on a task in which the three variables remained fixed over two minute periods but changed to new fixed values at the end of each two minute period. Subjects returned approximately one week after their first testing date to complete a retention task that was similar to the transfer task. The mean RMS error for the transfer task and for the retention task did not reveal any reliable differences between groups.

An additional dependent variable suggested by Gopher et al. (1975) was designed to test the operator's adaptability to a changing situation. In support of this dependent variable, Gopher et al. argued that vehicle operators must be able to cope with changes in system dynamics and in disturbance characteristics. Adaptive techniques that change these variables throughout training may better prepare the operator for variations in control demand. To test this idea, Gopher et al. examined the RMS error from the transfer task before and after the changes to different fixed values. The differences between the mean RMS error over the last 15 seconds of a two-minute period and the mean RMS error of the first 15 seconds of the following two-minute period were averaged for each subject over the three relevant change points. These data showed that frequency and gain adapted subjects performed better during transition periods than subjects who were not frequency or gain adapted during training. A similar analysis of the retention task did not reveal any reliable differences. Nevertheless, the transfer data supports the hypothesis that some adaptive training manipulations can help an operator learn to cope with changes in the external disturbances and in system dynamics.

Williges and Williges (1976) extended the previous study by investigating manual and automatic adaptations of forcing functions bandwidth. In a two dimensional pursuit tracking task the adaptive variable was adjusted either automatically or by the subject with a dual button keyboard adjacent to the control stick. For the control condition the task was fixed at the maximum bandwidth used in the adaptive schedules.

All subjects practiced to a bandwidth and error criterion and then transferred to a similar fixed task.

Transfer performance was best for the manually adapted group and worst for the control group. The difference between the two was statistically reliable. The transfer performance of the automatically adapted group lay between those of the other two groups but was not reliably different from either. Although amount and type of training were confounded in this experiment, poorer group transfer performance corresponded to longer pre-transfer training, so that the superior performance of the manually adapted group cannot be attributed to more extensive pre-transfer practice. The data therefore demonstrate an advantage for the bandwidth adaptation.

Feedback Variables

Smith *et al*. (1974) developed an adaptive paradigm based on displayed information about the probable future course of the controlled cursor in a one dimensional tracking system. Displays that present this type of information have been widely investigated under the rubric of predictor displays, and have been shown to substantially decrease the difficulty of complex control tasks (Kelley, 1968; Kennedy, Wulfeck, Prosin and Burger, 1974). The predictive information was computed by a fast-time model of the system dynamics on the basis of current system state and certain assumptions about the operator's behavior. The experiment by Smith *et al*. (1974) is the first to examine a predictor display as a learning rather than a performance aid.

The tracking task simulated the descent of a jet training aircraft along a glide slope. It was performed in an aircraft simulator in which the standard flight instruments had been replaced with a side looking cathode ray display that depicted the desired glide slope, an error tolerance envelope, a controlled cursor representing the aircraft, and a line that showed the predicted track of the controlled cursor. Each trial started with the simulated aircraft on final approach in level flight. Approximately eight seconds later the controlled cursor reached the glideslope, and the subject then tracked the glideslope to its point of intersection with the runway. Each trial lasted approximately sixty seconds.

Ten groups of subjects were tested. One was a control group that received no predictor information, and the other nine were experimental groups that trained under various conditions of predictor information. The experimental schedules were made adaptive by presenting the predictor information only when a subject's performance fell below a prespecified standard so that, during early training the predictor information was available for most of the time, but was presented for decreasing periods of time as the subject improved. The nine experimental conditions were established by completely crossing two variables. One variable was the criterion for presenting the predictor information, which would automatically appear only if the error was predicted to be outside of the tolerance envelope in zero, five, or ten seconds. The other variable was defined by the duration of prediction, which could be five, ten or twenty seconds. After practicing a prespecified number of trials, subjects transferred to a test condition that was identical to the control training condition. Integrated altitude error on the transfer task was used as the primary dependent variable.

Some of the experimental groups demonstrated superior transfer performance. Long predictor spans and early anticipation of error allowed the best transfer performance, while conditions with short predictor spans and those in which the predictive information appeared only when the tolerance envelope had been exceeded, were generally no better than the control condition. Unfortunately it is not possible to determine whether the adaptive feature of the schedules contributed to the superior performance of the better experimental groups. Predictor information, presented in a non-adaptive mode during the training phase, might have demonstrated similar advantages. An extra control group in which predictor information was available throughout training, regardless of the subject's performance, could have resolved this issue, and is recommended for future studies of this type. Nevertheless, the experiment does tentatively support the application of feedback adaptations in training.

A flight experiment by Gilson and Ventola (1976) has demonstrated the value of adaptive augmented feedback for aircraft landing instruction. These investigators mounted a tactual display on the control yoke of a light airplane to give student pilots pitch error information during six takeoff and landing trials with the display, and then another six without it. A second group flew their first six trials without the display and their second six, with it. The tactual display clearly aided landing performance while it was active. In addition, a comparison of the two groups' performances on the trials in which the tactual display was not used, indicated that practice with the display aided later landing performance without it.

Adaptive supplementary feedback has also been tested, under the rubric of augmented feedback, with standard pursuit rotor and other tracking tasks. Gordon and Gottlieb (1967), and Gordon (1968) used a pursuit rotor to examine the effects of supplementary visual feedback that was available during learning trials only when their experimental subjects were off-target. The experimental group's subsequent performance on a similar transfer task with no supplementary feedback was reliably superior to that of a control group that had practiced without supplementary cues. Williams and Briggs (1962) obtained a similar result in a control knob tracking equipment that tested off-target aural information.

DISCUSSION OF RESEARCH AND OF THE ADAPTIVE TRAINING CONCEPT

Adaptive training research has provided very little support, in comparison to the magnitude of the research effort, for the application of perceptual and response adaptations to applied training situations. The only unequivocal and statistically reliable data to demonstrate their effectiveness was obtained with an atypical control task (Gaines, 1967). Several of the experiments that apparently support AT principles have methodological problems that are critical enough to discount the conclusions drawn from them. In general, the research related to perceptual and response adaptations has produced little conclusive evidence for or against AT. In contrast, the meager data on feedback adaptations show a consistent and statistically reliable advantage for AT (Gilson and Ventola, 1976; Smith *et al.*, 1974). Further support for augmented feedback adaptations is available from the more theoretically oriented augmented-feedback research (Gordon, 1968; Gordon and Gottlieb, 1967; Williams and Briggs, 1962).

The AT literature has failed to answer some basic and critical questions. In particular, is the concept well-founded and worth further effort? If it is, what manipulations are likely to be successful? Research to this date has had a strongly applied emphasis that has encouraged investigators to concentrate on aspects of AT that are most appropriate to their immediate concerns. As commendable as this may appear, it has not established the theoretical or conceptual basis that is essential for orderly development of AT. The following discussion rationalizes the AT data with other psychological theory and data in order to construct a sound conceptual basis for the research.

The idea that an adaptive algorithm should provide an optimum schedule for skill acquisition has been based on the evidence that demonstrates wide individual differences in skill acquisition and on the belief that complex skills are comprised of simple skills. There are however other principles within the motor skill literature that bear on the AT model. Although these principles gain theoretical and empirical support from a variety of sources, they all have implications for important features of AT.

The first principle to be noted is that skilled behavior can develop only in the presence of consistent and lawful stimulus-response relationships. Contemporary motor skill theories that are incompatible in some respects (Adams, 1971; Pew, 1974; Schmidt, 1975) have, as one point of agreement, the need for consistent stimulus-response relationships. Inconsistent stimulus-response relationships would presumably inhibit development of the perceptual trace (Adams, 1971), or would interfere with development and selection of the appropriate motor program (Pew, 1974) or schema (Schmidt, 1975). Within the AT context procedures that force trainees constantly to develop new strategies or responses to unchanging stimulus demands or that abruptly change stimulus demands without consequent changes in response requirements are unlikely to be effective.

A related principle is that skills learned in one situation can be transferred, with partial performance loss, to similar situations. Holding (1976) has outlined the transfer relationships that can be expected between perceptual-motor tasks that vary along stimulus or response dimensions. Within AT, the task to be adapted should be changed in a way that enhances positive transfer from its easy to its more difficult versions. The choice of adaptive variable is important because not all manipulations of difficulty are equally likely to enhance skill acquisition. Positive transfer from easy to difficult versions of the task is undoubtedly essential for the adaptive schedule to be effective.

A third important principle is that repetition of the stimulus-response relationship is necessary to establish all but the most trivial behaviors. From the principle of transfer, the repeated behaviors need not be identical, but must be similar in important respects. Schedules that do not allow sufficient repetition, or force repetition of unrepresentative responses, are unlikely to facilitate skill acquisition.

The fourth principle listed here is that some complex tasks can be segmented into several simple tasks. This principle has been exploited in the part-whole training paradigms in which practice with simple segments of a task have facilitated the acquisition of the whole task (Adams, 1960; Fitts & Posner, 1967; Welford, 1968). This procedure can be ineffective if, through segmenting the task, its most difficult aspects are lost, or if the segments do not teach skills that can be used to perform the whole task. In addition, some tasks are not sufficiently difficult to warrant segmentation into easier components. These observations indicate that for AT, the tasks should be difficult enough to warrant this type of intervention, and the adaptive variable should be chosen so that when the trainee practices simple versions of the task, he will learn skills that he will use when performing the criterion version of the task.

The final principle is related to the feedback that the trainee receives about his behavior. Armstrong (1970a) has distinguished motivational and guidance feedback. The emphasis that some contemporary theories place on the role of guidance feedback (Adams, 1971; Schmidt, 1975) is supported by the research of Trowbridge and Cason (1932) and of McGuigan (1967) which indicates that more precise guidance information facilitates the acquisition of a discrete motor skill. Intrinsic response-produced feedback may be adequate to learn and perform the task, or supplementary feedback such as error information from an instructor may be needed. Nevertheless feedback of an appropriate type probably is essential for skill acquisition.

These principles are to some extent interrelated and to list them all is to occasionally restate a point. Nevertheless each has been deemed important in several motor skill contexts and together they account for the most common relationships in skill acquisition. As a first approximation any AT procedure that violates one or more of them is unlikely to be maximally effective. These principles are used in the subsequent discussion of research to examine the potential of different adaptive variables, the role of feedback, parameters of the adaptive logic, and criterion task difficulty. Adaptive manipulations will be discussed again under the headings of response, perceptual, and feedback variables. Both AT and transfer of training data are used to assess the potential merit of various adaptive manipulations. The discussions of adaptive logic parameters and of criterion task difficulty will be primarily conceptual because there is little empirical work related to these issues.

Adaptive Variables

AT researchers have been primarily concerned with optimizing task difficulty throughout training. They have generally treated difficulty as a single dimension and have apparently assumed that any convenient manipulation of task difficulty will be satisfactory. Difficulty has been extensively investigated as an independent variable, but reviews of this work indicate that changes in the several variables that can be used to manipulate task difficulty have dissimilar effects on skill acquisition (Day, 1956; Holding, 1962). Task difficulty is more appropriately considered as a dependent variable that is operationalized by ordering scores on some measure of performance. Instead of considering it as a single dimension under the questionable assumption that it has consistent effects on skill acquisition, each of the adaptive variables that can influence task difficulty will be evaluated separately.

Although response, perceptual, or feedback adaptations almost certainly have different effects on learning, their relative merits as adaptive variables have rarely been discussed. The nature of the criterion task in particular seems relevant to the choice of adaptive variable. For example, because control of an inherently unstable rotary wing aircraft during hover is primarily a motor skill problem, response or perceptual adaptations that change response difficulty seem to be the most appropriate. In contrast, landing a fixed wing aircraft in poor visibility is difficult primarily because of the imprecise nature of the visual cues, so that a feedback adaptation seems to be most appropriate. The recommended adaptation in each of these examples is preferred because it allows the task to be varied over a greater range of difficulty than the alternate adaptations. This argument indicates that the choice of response, perceptual, or feedback variables should be based, to some extent at least, on the nature of the criterion task.

In addition to neglecting any discussion of the type of variable that should be adapted, AT researchers generally have failed to justify the specific variables they have chosen. In particular the nature of the transfer between the task variations defined by the adapted dimensions has been ignored. Equal increments in difficulty might be obtained by varying any single variable, or any combination of variables, but different manipulations could have quite different effects on skill acquisition. With some manipulations practice at one level of difficulty could conceivably interfere with performance at higher levels. It seems reasonable to expect that an adaptive manipulation will facilitate skill acquisition only if transfer from easy to difficult task variations is both positive and substantial.

The rationale for this expectation can be clarified with an example of a hypothetical transfer of training experiment. The fundamental AT assumption is that training on an appropriate easy task can better prepare an operator for a difficult criterion task than can equivalent training on the criterion task itself. This could be tested in an experiment in which subjects transferred to the criterion task after some training on the easy task. A control group that trained throughout on the criterion task would be necessary for comparison. That the experimental group's pre-transfer task is easier than the criterion task would be demonstrated by the fact that their performance during the pre-transfer phase is better than the control group's performance on the corresponding criterion task trials. Possible data trends are shown in Figure 2, and in particular, two alternative trends are shown for the experimental group's transfer data. Although both of the experimental group's transfer trends demonstrate positive transfer in that the early transfer trials reflect better performance than do the control group's early trials, only trend B demonstrates an advantage for prior training on the easy task. In contrast, data that follow trend A reveal that trainees learn more about the criterion task by practicing the criterion task than by practicing the easy task.

In some transfer of training studies transfer has taken place along a dimension that has elsewhere been used, or might be used, as an adaptive variable. The data from these transfer experiments seems relevant to a discussion of AT. It is true that the adaptive and transfer designs differ noticeably in that adaptive designs employ several small "easy to difficult" steps while transfer designs employ only one. Although size and number of steps could well be critical factors, a variable's influence in a multi-step experiment is likely to correlate with its influence in a one-step experiment. Furthermore, the comparability of data from experiments with few or many steps has been accepted, at least implicitly, by those experimenters who were influenced by Briggs' (1961) two-step experiment.

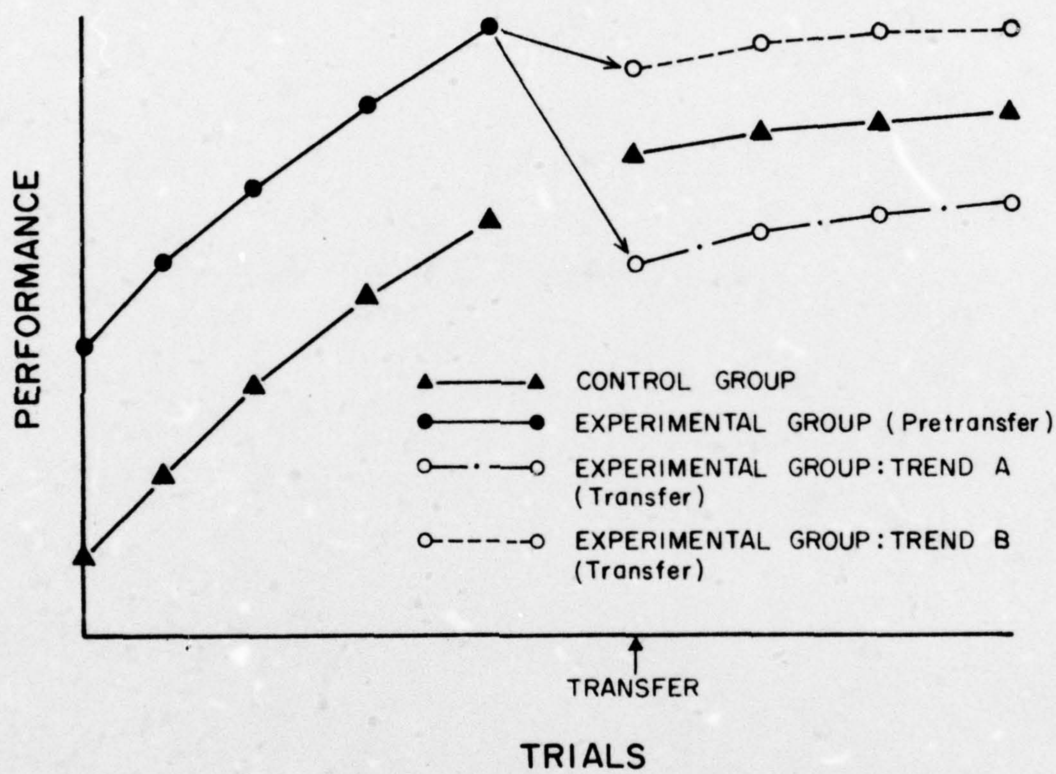

Figure 2. Hypothetical transfer of training data. Trends A and B represent alternate possible transfer trends for the experimental group.

Thus transfer of training data will be combined with the previously discussed AT data to evaluate the potential merit of some adaptive manipulations. Sufficient data are available from transfer and adaptive studies to make at least a preliminary judgment about the potential of system order, gain and lag, forcing function, and augmented feedback manipulations. An additional variable called percentage of display pursuitedness has never been used as an adaptive variable but will be considered because it is relevant to tracking behavior and because it can be used to represent a dimension along which tracking difficulty can be varied.

Response Variables

System order has emerged as the most popular adaptive variable, but transfer data indicate that it is unlikely to provide an effective training manipulation. Lincoln (1953) showed that practice on a zero-order system was less adequate preparation for subsequent tracking on a first-order system than was practice with the first-order system. Briggs, Fitts and Bahrick (1958) similarly showed that practice with a first-order system produced poorer performance on a second-order system than did equal practice with the second-order system. Transfer from a combination zero, first, and second-order system to a pure second-order system also failed to show any advantage for prior training on the lower-order system (Holland and Henson, 1956).

Experimental comparisons of quickened and unquickened displays have produced similar results (Dooley and Newton, 1956; Goldstein, 1961). Of the

AT experiments in which system order has been adapted (Briggs, 1961; Crooks, 1973; Gopher et al., 1975; Hudson, 1962, 1964; Norman et al., 1972) only the two by Hudson that were criticized on methodological grounds, revealed any advantage for the adaptive manipulations. Furthermore, Crooks (1973) has shown that order manipulations can retard skill acquisition: an observation that is supported by unreliable trends in the transfer data from Gopher et al., (1975). System order therefore appears to be an inappropriate choice as an adaptive variable.

Transfer of training data from Rockway, Eckstrand and Morgan (1956) indicate that gain is unlikely to be a useful adaptive variable. In this experiment, subjects practiced on one of three gain conditions and transferred to the highest and most difficult gain condition. There were no perceptible differences between the transfer performances of the three groups. The AT data are also not very encouraging. Gopher et al., (1975) were able to show an advantage for gain with their exploratory dependent variable, but unreliable trends in their overall transfer scores indicated that FT was better than AT in which gain was manipulated.

Because system lag is inherent in any tracking system, has a well defined relationship to tracking difficulty, and can be easily manipulated, it appears to be a potentially useful adaptive variable. It has been tested in two AT experiments, and in both it was combined with a system gain manipulation (Norman, 1973; Norman et al., 1972). Neither of these experiments provided acceptable data. However a transfer of training experiment by Levine (1953) provided some relevant data that discourages the use of system lag as an adaptive variable. Transfer performance on a no-lag condition for a group that had practiced previously with a lagged system was no better than that of a group that had remained on the lagged system throughout the experiment. Nevertheless these data must also be supplemented with results from other experiments before firm conclusions can be drawn about the potential value of lag as an adaptive variable.

Theoretical considerations indicate that response manipulations are unsuitable adaptive variables. As defined earlier, response manipulations are those in which the operator must learn to generate new responses to unchanging stimulus information. Holding (1976) has observed that there is a high probability of negative transfer in this type of situation. This possibly results from the fact that it violates the principle of consistent stimulus-response relationships. Although response variables can be used to change task difficulty, this type of manipulation seems unsatisfactory for training purposes.

Perceptual Variables

Forcing function adaptations have been popular, but the supporting data are inconclusive. The successful amplitude manipulation used by Gaines (1967b) was tested with an unrepresentative tracking task. The data provided by Lowes _et al_. (1969) and Norman _et al_. (1972) are suspect because of methodological problems with those experiments. Gopher _et al_. (1975) could demonstrate an advantage for their bandwidth manipulation only with their exploratory dependent variable chosen to examine performance stability.

In contrast, the evidence against forcing function adaptations is impressive. Wood (1968) found that his amplitude manipulation was less effective than his non-adaptive manipulation and Gopher *et al.* (1975) obtained a null result with orthodox transfer and retention measures in comparing a bandwidth adaptation with a control condition. The degree of transfer between frequency and amplitude variations in transfer of training experiments employing a pursuit rotor (Ammons, Ammons and Morgan, 1954; Lordahl and Archer, 1958), was insufficient to encourage either frequency or amplitude adaptations. However it may be unwise to rely on a null result or on pursuit rotor data. Wood's result is noteworthy, but in view of the conflicting, although questionable data, judgment of forcing function adaptations should be delayed until more extensive data are available. Further transfer studies employing appropriate tracking apparatus could resolve this question.

Perceptual manipulations theoretically are more sound than response manipulations because they progressively extend the repertoire of stimulus-response relationships rather than change them. Adaptive training with a perceptual variable is analogous to the type of part-whole training that can sometimes facilitate acquisition of a complex task through prior training with simple components of the task (Adams, 1960; Fitts and Posner, 1967; Welford, 1968). If the analogy is valid, appropriate simple elements of the complex task that can be properly integrated or sequenced to ensure positive transfer between various difficulty levels must be identified to establish the adaptive schedule. Although theories of skill acquisition might be expected to indicate suitable segmentations of the complex task and, therefore, the appropriate adaptive variable, contemporary theories seem inadequate for this purpose. The selection of an appropriate perceptual manipulation remains, for the present at least, a predominantly empirical problem.

Feedback Variables

Augmented error information that is concurrent with the response, that tells the subject when he is off-target, and that guides the operator to the correct behavior, has been tested twice (Gilson and Ventola, 1976; Smith et al., 1974), and in both experiments transfer performance was enhanced by the adaptive feedback manipulation. Augmented-feedback studies employing concurrent, off-target feedback also support the use of feedback adaptations (Gordon, 1968; Gordon and Gottlieb, 1967; Williams and Briggs, 1962).

Other transfer-of-training studies have tested concurrent, augmented-feedback that informs the subject when he is on-target. Some of these experiments have demonstrated benefits for augmented-feedback (Gordon and Gottlieb, 1967; Karlin, 1965, Karlin and Mortimer, 1963; Kinkade, 1963; Seashore, Underwood, Houston and Berks, 1949; Williams and Briggs, 1962) while others have produced null results (Archer, Kent and Mote, 1956; Archer and Namikas, 1958; Bilodeau and Rosenquist, 1964; Sheldon and Bjorklund, 1966).

The greater consistency of evidence in favor of the off-target manipulation may have resulted from the fact that it is inherently adaptive in that, as the subject learns the skill, the augmented-feedback is presented for decreasing periods of time. Thus transfer to a non-augmented feedback condition will, for a skilled subject, constitute a less substantial task change than if on-target information had been augmented during acquisition. As positive transfer between tasks that require identical responses is related to similarity of stimuli (Holding, 1976), the off-target manipulation seems to be the most appropriate.

The data from feedback studies are sufficiently encouraging to warrant further research. In particular, the benefits of on and off-target schedules, various types and parameters of command and predictor indicators (eg. Roscoe, Eisele and Bergman, 1975), and differing error limits should be examined.

Percentage of display pursuitedness, a concept introduced by Briggs and Rockway (1966), could provide another useful perceptual manipulation. Although tracking displays are generally classified as pursuit or compensatory, Briggs and Rockway established a display that was partially pursuit and partially compensatory. Thus a display that is 25% pursuit, is also 75% compensatory. Pursuit displays are easier to track than compensatory displays (Poulton, 1974) so that display pursuitedness could also be used as a dimension of difficulty for control tasks. Although this variable has not yet been manipulated in any AT experiments, it could be used to teach vehicular control activities that are inherently compensatory, but could be simulated as pursuit tasks. Tracking an aircraft along the extended centerline of a runway in the presence of gusting crosswinds is one example of a task that is inherently compensatory, but could be represented as a pursuit task in an aircraft simulator.

One transfer of training study (Gordon, 1959) supports the use of percentage of display pursuitedness as an adaptive variable. In that experiment, subjects who were initially trained on a pursuit task performed better on a compensatory task than subjects who had trained throughout on the compensatory task. There is however, some inconsistency in the available data. A similar experiment by Briggs and Rockway (1966) revealed no performance differences on a compensatory transfer task for groups trained with degrees of display pursuitedness ranging from zero to 100%. It may be relevant that Gordon used a spring loaded control while Briggs and Rockway used a quasi-isotonic control. If transfer from pursuit to compensatory tasks depends on proprioceptive cues learned in the pursuit task, the system used by Briggs and Rockway would produce less transfer than the one used by Gordon. This hypothesis needs to be resolved empirically as a prelude to investigation of display pursuitedness as an adaptive variable.

The feedback variables discussed so far provide the operator with information that is concurrent with his responses and enhances the information he would normally receive about the nature of his control errors. The importance of the second characteristic is supported by contemporary motor skill theories that stress the guidance role of information feedback in skill acquisition (Adams, 1971; Schmidt, 1975). The expectation that the concurrency of feedback is important is derived from discrete motor skill learning research (Bilodeau, 1956; Boulter, 1964) in which subjects performed some activity during the delay between a response and its guidance feedback. In Bilodeau's experiment, guidance feedback to each response was delayed while the subject made one or more other responses to which feedback was also delayed by the same number of responses. Execution of responses in the feedback delay interval degraded performance in the acquisition trials. Boulter's experiment showed that verbal or motor activity inserted in the feedback delay interval could degrade performance after feedback was withdrawn. Although activity in the feedback delay interval does not degrade transfer performance after extensive learning (Lavery, 1964; Lavery and Suddon, 1962), it does seem to interfere with early learning.

Other experiments (Bilodeau and Bilodeau, 1958; Bilodeau and Ryan, 1960; Boulter, 1964; Saltzman, Kanfer, and Greenspoon, 1955) have not shown any acquisition or transfer effects of varying an unfilled delay but the findings of Bilodeau (1956) and Boulter (1964), that activity during the feedback delay does interfere with acquisition and transfer, seems more relevant to continuous tracking behavior. Continuous skills would similarly suffer from interference by intervening responses if feedback was delayed. Augmented-feedback is likely to be an effective adaptive variable, and the potential to make it concurrent with the response may be an important advantage that automatic feedback systems have over human instructors.

However not all types of feedback are likely to be equally effective. Although many research workers in AT have assumed that the motivational effects of feedback are critical in skill acquisition (McGrath and Harris, 1971), there is little evidence to support this assumption. Only Norman (1973) has tested it within the AT research. He allowed some of his subjects to monitor a meter that displayed concurrent information about their performance. This group learned the tracking task more quickly than a similarly trained group that was denied the meter information. Unfortunately the result was confounded by sampling biases. The feedback group contained a substantial number of naval recruits while the non-feedback group consisted only of college students. The effects of these sampling differences is unknown.

Other AT experiments in which motivational feedback was augmented (Wood, 1969; Crooks, 1973) did not compare feedback to no-feedback conditions. From the results of a transfer-of-training experiment Smode (1958) has argued that motivational feedback does facilitate the acquisition of tracking skill. However Smode used concurrent, on-target feedback that would seemingly have helped to guide the subjects to the desired responses as well as to motivate them. The effects of motivation on the acquisition of tracking skill have been difficult to demonstrate (Bilodeau and Bilodeau 1961). Some appropriate motivation undoubtedly is essential to activate behavior and to focus attention on the task but increments in motivation about a certain level apparently do not substantially facilitate learning (Hulse, Deese, and Egeth, 1975).

To be maximallv effective feedback should both guide the subject's responses and be concurrent with them. This type of feedback could be used within AT either as an adaptive variable or as a transfer variable that is fixed at an optimal configuration during initial training in conjunction with a schedule that adapts some non-feedback variable. Both types of schedules could prove to have a potent influence on skill acquisition.

Parameters of the Adaptive Logic

Adaptive training has been compared elsewhere to human instruction of high-level subjects in which students are guided through sub-topics of graded difficulty (McGrath and Harris, 1971). The analogy is appropriate in that the human instructor, by some casual or formal process, will determine the number and size of steps in difficulty, and will influence the rate at which the student makes them. The stepping rate is influenced by the acceptable performance standard set by the instructor and by the intervals separating successive assessments of student performance. This rate will tend to be low if the student's performance must improve substantially before he is allowed to progress or if the summaries of his performance that determine whether he will be allowed to advance or not are separated by long intervals. The parameter that defines size and number of steps and the two that define the stepping rate are explicitly programmed into the adaptive logic as the step size, the performance limits, and the performance measurement interval.

Although the analogy between human and automatic adaptive instruction has been used to support the validity of AT (Kelley, 1969b), it is considered here as no more than an illustration. Its particular value in that role is that it clarifies the questions that should be asked about the adaptive logic. What are the optimal size and number of increments in difficulty? How frequently should the trainee be assessed and how well should he be expected to perform before he is allowed to advance? Should he be allowed to return to easier versions of the task if his performance deteriorates below some minimum standard? Although these questions have been inadequately investigated, they are important enough for their implications to be examined.

The number and size of steps in difficulty has ranged from a few large steps (e.g. Lowes et al., 1968) to many small steps (e.g. Crooks, 1973). Norman et al. (1972) compared conditions with many small steps to those with few large steps by comparing automatic and manual adaptations. A manual group with adapting system order did not perform as well as the relevant automatic group, and other non-reliable trends for their forcing function and their combination gain/lag adaptations favored the automatic groups. In support of these observations, transfer theory suggests that steps above a critical size are not optimal. Holding (1976) has noted the high probability of negative transfer with all but very small changes in response requirements where the stimulus is essentially unchanged. In addition the principles he outlines suggest that positive transfer will be small if perceptual and feedback variables are changed substantially. Thus transfer theory does suggest that the step size can be too large, but does not indicate its critical size for any variable. These values will undoubtedly have to be determined empirically.

The stepping rate is influenced by the performance limits that determine whether the trainee will advance and by the performance measurement interval. By an earlier stated principle that repetition is essential to establish all but the most trivial responses, stepping rate should be low enough for the trainee to repetitively practice each of the skill segments along the easy-to-difficult dimension. However a very low stepping rate could force the trainee to practice some of the skill segments for an unnecessarily long time.

Unfortunately it is difficult to translate this conceptual argument into specific values for the adaptive logic. Empirical tests of the variations in performance limits (Bancroft and Duva 1969; Crooks, 1973) have not produced reliable differences between the experimental conditions. Presumably a performance standard that approximates that required in the operational situation will be advantageous in that it is more likely to encourage the appropriate response habits and strategies. If this criterion is accepted for establishing performance standards, the freedom to establish an optimum stepping rate lies in varying the performance measurement interval. Only Norman (1973) has tested this parameter, but methodological problems with his experiment makes his data difficult to interpret. At present there are no clear principles to determine the optimal stepping rate so that, within operational AT systems, it will have to be established by trial and error.

The final question related to the adaptive logic is whether trainees whose performance temporarily deteriorates should be allowed to return to easier segments of the adaptive schedule. There seems to be no theoretical argument that bears directly on this issue. One empirical test (Crooks, 1973) has shown that trainees who were not permitted to return to easier versions of the task learned more efficently than a comparable adaptive group that was. Note however, that the non-returning schedule was not more efficient than a nonadaptive schedule and the adaptive variable was the system order manipulation that has been criticized earlier in this review. Therefore the relevance of this result is debatable.

Any or all of these parameters of the adaptive logic could affect the efficiency of AT. Further research must be undertaken to establish optimal values, and to derive principles for determining them in advance if AT procedures are to approach their potential effectiveness.

Criterion Task Difficulty

Adaptive training could be useful for two distinct applications. The first is one in which the criterion task can be learned under FT, but the use of AT speeds the process. This is consistent with the assumption that control tasks can be learned more efficiently if they are presented at an optimum level of difficulty (Kelley, 1969b). In an alternate application, AT could enable operators to learn a control task that is too difficult to learn under FT.

Gaines (1967a) has suggested that some tasks can be so far beyond the current skill of the trainee that even extended fixed practice does not permit him to improve. This might happen if the task was so difficult that the operator was out of control throughout the training period. Practice with an approprate easier task, as in an adaptive schedule, might help the trainee develop skills that would transfer to the criterion task, thereby bringing it within the trainee's adaptive skill range. This application of AT would allow an operator to achieve a level of proficiency that he could not attain under FT, while the first application would not gain any advantage over FT in final level of performance, but would help the trainee attain that level more efficiently.

The effectiveness of AT for these two applications should be tested with slightly different experimental designs. To show that AT is more efficient than FT for achieving a criterion performance, subjects should be trained to that criterion and the time taken to achieve it could be compared. This type of design was appropriate for all of the AT experiments that have been reviewed because the experimental tasks could be learned under fixed schedules. However only Crooks (1973), Norman et al. (1972), and Norman (1973) trained their subjects to criterion. Others examined training or transfer task performance after a set amount of training. The danger of this approach is most clearly illustrated in the report by Bancroft and Duva (1969). Subjects in that experiment practiced for so long that even the slowest learning groups had attained maximum performance well before the end of the training trials. Therefore the transfer test could not have been expected to reveal differences due to training methods. This design would have been appropriate if a task that was too difficult to learn under FT had been used. The extended training time should have provided ample opportunity for the subjects to improve as much as each of the fixed and adaptive schedules would allow. Differences between adapted and fixed groups at the end of training or on the transfer task would attest to the relative merits of the different training methods for that task.

Adaptive training researchers have hitherto seemingly failed to discriminate the application of AT to control tasks that can be learned under FT and those that cannot. As the choice of the experimental design is related to this issue, it is important to distinguish the two types of task. Non-optimal experimental designs can provide important information, as some in AT have done (e.g. Gaines, 1967b; Smith et al., 1974) but the information is devalued to the extent that the experimental design departs from optimality. Future AT research could benefit appreciably from greater awareness of this problem.

ADDITIONAL CONCERNS

Dimensionality of Performance Measures

Experimentation with adaptive techniques has been dominated by tracking tasks. The most popular performance measure in this task is RMS tracking error. The study by Gopher et al. (1975) has called attention to the fact that composite error scores on a multidimensional or high-order tracking task may not reflect a undimensional ability factor of the trainee. In this study, with a two dimensional pursuit tracking task, the vertical axis was clearly inferior to the horizontal axis as a result of reduced stimulus-response compatibility on that axis. Training on the vertical axis progressed at a slower rate even after each axis was equated for difficulty. These findings suggest that the employment of a composite error score, such as vector error, or average RMS, will create a sub-optimal adaptive procedure, because the rate of progress will be too slow on the easy axis and too fast on the difficult one. In more general terms it can be argued that, for multidimensional tasks where dimensions are not closely related and do not symetrically covary with task difficulty, separate performance measures or an appropriate weighting function should be developed to assure proper adaptive sequencing on each dimension.

Changing the Adaptive Equation

Adaptive adjustments are assumed to continuously reciprocate the progress of learning. Once the adaptive variable and the performance measure are defined the relationship between them is formulated through the adaptive equation. In all AT studies reviewed in this paper only one adaptive equation was employed throughout training. Thus it was implicitly assumed that the relationships between AT variables remain constant across the range of empirical values employed during training. This is a very powerful assumption that can be challenged.

An alternative suggestion is that an equal change in the adaptive variable will have a different impact on task difficulty in early as against late stages of training. That is, the relationship between variables in the adaptive situation may change during the course of learning. This argument is supported by empirical reports of S-shaped functions relating performance increments to time-on-task in many learning tasks. Employment of a single unchanging adaptive equation throughout training may introduce a considerable amount of rigidity to the adaptive procress, thus detouring it from its optimum course. As none of AT studies has addressed this issue, its possible relevance to the construction of adaptive schedules cannot be evaluated. It may be advantageous to construct two adaptive loops instead of one. The additional loop would function as a higher level, supervisory loop that would monitor the general progress of learning, and change if necessary, the adaptive equation in accordance with some model of training. The programming and management of such double loop systems is well within the capabilities of the current computer aided instruction (CAI) technology. The literature is however, notably deficient of empirical work on this type of system and further research is recommended.

The Role of the Instructor

As a final note, it may be worthwhile to address a misconception that some AT researchers seem to have assimilated from naive thinking about other instructional uses of computers. In a first rush of enthusiasm some ardent supporters of CAI speculated on its potential as a complete instructional system in which there would be no need for human instructors. CAI is often attacked on the basis of this view, even though it does not generally hold a respectable position among CAI personnel. It does however, seem to pervade the thinking of AT researchers.

During the AT symposium reported by McGrath and Harris (1971), conferees lauded the potential for automated instruction to supersede the human instructor. The expense and the inability of human instructors to react optimally in all situations were offered as reasons for preferring fully automated training. CAI in all of its various forms should be placed in a more balanced perspective. It has many specific advantages, but none of them imply that the human should be designed out of the instructional process. As advancing technology is making a completely computerized instructional system progressively more feasible to implement, a brief defense of the human instructor's unique role seems timely.

Role modelling is one process of instruction that would be neglected in a fully computerized instructional system. Carkhuff (1971) has noted that identification with a suitable role model substantially influences behavior. He further believes that modelling is the most critical source of learning in any training program and that the trainer is the key model. What behavior is modified by the modelling process depends on its availability, its functional value, and the attractiveness of the model (Secord and Backman, 1974). Mere exposure to the standards of others is apparently sufficient, in some circumstances, to modify behavior (Longstreth, 1968). The negative consequences of identifying with machines, alluded to by Eriksen (1963), further supports the notion that CAI can be detrimental if it is permitted to dominate the instructional process.

Optimally, CAI can relieve the instructor of specific tasks that are tedious or difficult so that he may devote his energy to the uniquely human aspects of instruction, but it cannot provide a total educational experience. Properly validated AT procedures could substantially improve training efficiency, but should be considered only as one effective training aid that the skillful instructor can use in conjunction with other available training aids.

SUMMARY

Although adaptive training has generally been accepted within engineering psychology and in some applied settings, there are few data to attest to its advantages for teaching vehicular control skills. Research has suffered primarily from methodological difficulties and from limited conceptualization of the many facets of the adaptive paradigm. In spite of our generally negative view of much AT research, other motor skill theory and research and a few AT experiments indicate the the method could be useful. This review has established a conceptual framework for AT to guide the future research that is essential to test and develop the method.

In particular, the choice of the adaptive variable bears on the likely success of the training manipulation. However the choice of adaptive manipulations generally has not been justified and often seems to have been a matter of convenience. Researchers rarely have discriminated between difficulty manipulations in general and those that can be expected to facilitate skill acquistion. Response manipulations have been popular but both theory and data suggest that they will disrupt rather than facilitate skill acquisition. The data related to perceptual manipulations are only slightly more encouraging but a theoretical analysis suggested that appropriate perceptual manipulations could be effective. The perceptual manipulations that allow practice with task segments that are important in the performance of the whole task are likely to be most effective. The data related to feedback

variables were promising. Adaptations that initially decreased the difficulty of the criterion task with concurrent off-target augmented-feedback that guided the trainee towards the correct response have been tested successfully. Contemporary theories and substantial skill acquisition data support the confidence in this type of manipulation.

Parameters of the adaptive logic were examined for their influence on skill acquisition. These parameters have not been adequately researched, although some observations were based on theory and limited data. Transfer theory indicates that step size of the difficulty manipulation can be too large, but it was not possible to estimate the critical size. Stepping rate is influenced both by the performance limits that determine whether a student can advance in the adaptive schedule and the performance measurement interval. This rate should be established by balancing the competing demands of moving the trainee through the adaptive schedule as economically as possible and of allowing him sufficient time to learn the relevant skills at each of the steps. Although there are no compelling principles for choosing any specific values, performance limits that approximate those that are relevant in the operational situation should encourage appropriate response habits and strategies. Optimum performance measurement intervals are probably specific to each situation and at this stage at least will have to be determined empirically.

Criterion task difficulty is another aspect that has received sparse attention within the experimental literature. Two types of tasks were identified in this review; those that could be learned under non-adaptive schedules but would be learned more efficiently under adaptive schedules, and those that were so difficult that they could not be learned under anything but an adaptive schedule. The distinction is important because it demands slightly different experimental tests. The test for the former situation should be designed to show that one of the schedules leads to criterion performance more quickly than the other, while the test of the latter situation should allow the adaptive schedule to demonstrate any performance advantage it may encourage after extended training.

In conclusion, a substantial body of research has not clearly demonstrated the value of AT, nor has it clearly indicated that the technique is ineffective. To reasonably test it a far more comprehensive program of research is required. Other motor skill theory and research suggest that such a research program could demonstrate benefits for AT. The research approach outlined in this review could establish a worthwhile data base from which the validity of AT as a training method could be judged.

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The adaptive training research is described and evaluated. A critical examination of the various experiments reveals that there is less support for the application of adaptive manipulations to applied motor skill training than is generally believed. Some apparently favorable experiments have methodological and interpretive flaws that seriously weaken their conclusions. Other experiments that provide tenable support have characteristics that are unique in adaptive training research so that the generality (over)

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of their data is in doubt.

The limitations of the data prevent ~~any~~ firm conclusions being drawn about the efficiency of adaptive training. ~~However~~ a detailed analysis of motor skill theory and research indicates that some adaptive manipulations could be effective. Methodological and conceptual issues that are critical to successfully testing those manipulations are clarified in a discussion of the adaptive training concept. In addition, that discussion outlines several empirical tests ~~that are~~ needed to enable a more effective analysis of adaptive training. are also discussed.

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